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Bioeconomics of sexed semen utilization in a high-producing Holstein-Friesian dairy herd

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ABSTRACT

A bioeconomic, stochastic spreadsheet model, that included calculation of the net present value of the additional value of all future descendants resulting from increased selection intensity, was developed to study the profitability of using sexed semen in a high input–high output dairy herd. Three management strategies were modeled: (1) only heifers inseminated with sex-sorted semen and cows inseminated with unsorted semen; (2) both heifers and cows inseminated with sex-sorted semen; and (3) a reference scenario, in which all breeding females were inseminated with unsorted semen. A Monte Carlo simulation (@risk software, Palisade Corp., Ithaca, NY) was run to study the sensitivity of net profit and sexed semen advantage to key input parameters. Most input parameters were given truncated normal distributions, whereas the maximum numbers of inseminations in heifers and cows were given discrete distribution functions. The calculated intensity of selection accounted for the different numbers of dairy females born for each of the 100,000 iterations. Using sexed semen (X-sorted, female) was shown to be profitable, with insemination of both heifers and cows being most profitable. The returns on assets were higher when only heifers were inseminated with sexed semen (8.54% ± 2.94; ±SD) or all females were inseminated with sexed semen (8.85% ± 2.93) than when all females were inseminated with unsexed semen (8.38% ± 2.95). The range in net profit was most sensitive to the assumed distributions of milk protein price (€/kg), milk fat price (€/kg), cow pregnancy rate, fertilizer price (€/t), and concentrate price (€/t) when unsorted semen was used. When only heifers or both heifers and cows were inseminated with sex-sorted semen, the range in net profit was most sensitive to the same distributions, with fertilizer price and cow pregnancy rate in reverse order of sensitivity. However, the range in sex-sorted semen advantage (in net profit) when only heifers were inseminated with sex-sorted semen was most sensitive to the assumed distributions of cow pregnancy rate, sex-sorted semen pregnancy rate as a percent of unsorted semen rates, standard deviation of index, additional cost of sex-sorted semen (€/dose), dairy bull calf price (€/head), and dairy heifer calf price (€/head). When both heifers and cows were inseminated, the order of importance of the last 2 inputs was reversed. This study highlights the relatively high effect of pregnancy rate and the genetic value of dairy bulls in determining the level of financial advantage from using sex-sorted semen in a dairy herd.

Key words: sexed semen, dairy herd, stochastic model, Monte Carlo simulation

INTRODUCTION

Sex-sorted semen technology is commercially available in many countries around the world, and is primarily used in dairy cattle breeding. However, adoption of sex-sorted semen for AI in dairy cattle has been limited by cost, low conception rates (Hutchinson et al., 2013), sexing accuracy (reviewed by Butler et al., 2014; Seidel, 2014), and in some countries the limited number of AI bulls available with sexed semen. Sexing technology has improved over the past decade and is likely to further improve in the future through more rapid sorting rates, improved conception to AI, increased sexing accuracy to almost 90% (Schenk et al., 2009; Healy et al., 2013), and decreasing relative cost of sex-sorted semen compared with conventional semen (Seidel, 2007). Consequently, the dairy industry is increasingly taking advantage of this innovative technology. Although a gap in fertility between conventional and sex-sorted bovine sperm still exists, the system is being continually refined to develop a sex-sorted product that retains sperm integrity to improve post-thaw sperm quality and field fertility compared with unsorted semen (Gonzalez-Marin et al., 2016; Lenz et al., 2016).

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Sperm are sorted by flow cytometry based on a 4% difference in DNA content between sperm containing X and Y chromosomes. Despite reliably producing a 90% sex bias, the fertility of the sex-sorted semen product is lower than that of conventional semen (DeJarnette et al., 2011). The negative implications of the reduced fertility of sex-sorted semen are amplified in grass-based seasonal systems of dairy production, in which a compact calving pattern is essential to maximize milk production from grazed grass compared with nonseasonal dairy production systems. Conception rates to first service with frozen-thawed sex-sorted semen are typically 75 to 80% of those achieved with conventional frozen-thawed semen (DeJarnette et al., 2009). However, in a recent large-scale pasture-based study, conception rates 87% of those achieved with conventional semen were reported (Butler et al., 2014). Sex-sorted semen may facilitate faster, more profitable, dairy herd expansion by increasing the number of dairy heifer replacements born (Hutchinson et al., 2013). Biosecurity can be improved by maintaining a closed herd during the period of herd expansion. In a nonexpansion scenario, sex-sorted semen may be used to increase the value of beef output from the dairy herd because fewer cows would be required to produce dairy replacements. The remainder of the herd could be bred to beef breed bulls with short gestation lengths. In addition, genetic response to selection could be improved through an increase in selection intensity. Ettema et al. (2011) showed that the improved genetic progress from the use of sex-sorted semen helped offset the losses caused by lower conception and estrus detection rates and had a minimal effect on postponing first insemination. Underlining the importance of the effect of sex-sorted semen on genetic merit in dairy herds, Ettema et al. (2017) reported that none of the scenarios modeled were profitable under Danish circumstances when the financial (profit) advantage from the increased genetic merit was not included.

Many factors including market, type of production, and other circumstances can affect the potential sex-sorted semen advantage (**SSA**); that is, the increased net profit (**NP**) or return on assets (**ROA**) achieved compared with using conventional semen. Hohenboken (1999) suggested combining sex-sorted semen with a crossbreeding program to maximize revenue from the herd's nonreplacement (sale) calves. Butler et al. (2014) suggested that the use of sex-sorted semen should be restricted to well-managed seasonal grazing herds that already achieve acceptable herd fertility performance.

Sex-sorted semen advantage depends on the market environment (e.g., prices and costs), management practices (e.g., breeding program), and technological efficiency (e.g., conception rate and accuracy of sexing semen). Previous studies have examined the independent influence of markets, such as milk or heifer prices (De Vries et al., 2008); management changes, such as conception rate and number of inseminations (Olynk and Wolf, 2007); and technology changes, such as producing genetically better-quality replacement heifers (Seidel and Garner, 2002). Heikkilä and Peippo (2012) used a linear programming approach and found the optimum economic combination for a Finnish 60-cow herd was to inseminate 10 heifers and 22 cows with unsorted semen, 8 heifers with sex-sorted semen, and to use 20 cows as embryo donors, which was the upper constraint for this technique.

Khalajzadeh et al. (2012) used stochastic simulation to study the effects of sex-sorted semen on genetic progress and reproductive performance of dairy cows. Three strategies were compared in that study: unsorted semen in cows and heifers (U); sex-sorted semen in heifers and unsorted semen in cows (H); and sex-sorted semen in both cows and heifers (CH). The widespread use of sex-sorted semen increased the average age of cows in all parities. Sex-sorted semen increased selection intensity in the milking cows' selection path, and this contributed to the genetic merit of future cows. On the other hand, sex-sorted semen had a negative effect on the reproductive performance of dairy cows. Generally, although the effect of widespread use of sex-sorted semen (CH) on genetic progress was significantly more than when its use was limited (H), CH decreased reproductive performance of dairy herds dramatically, and they suggested that H scenarios might be more appropriate in animal breeding programs.

De Vries (2017) stated that when genetic progress is not considered, sex-sorted semen is only profitable in the United States when the value of a heifer calf is at least $400 more than the value of a bull calf. The value of sex-sorted semen does not vary much per service number in heifers; therefore, if a second service with sex-sorted semen is not considered profitable, the first service is, at best, marginally profitable. De Vries (2017) suggested that sex-sorted semen is not profitable in US dairy cows unless the fertility is almost equal to that of conventional semen. Clearly, estimates of the profit advantage of using sex-sorted semen are sensitive to factors such as the price differential between female and male calves and differences in costs and conception rates for sexed versus unsorted semen. In addition, if the genetic merit of animals is known, sex-sorted semen is most likely to have a profit advantage when used on genetically superior animals, whereas it may offer little profit enhancement when used on genetically inferior animals. Therefore, the value of genetic information increases when sex-sorted semen is used.

McCullock et al. (2013) explored the environmental, management, and technology conditions where sex-sorted semen would be profitable in a typical 2,500-head Colorado Holstein dairy using a spreadsheet budgeting approach. Market variables such as the added cost of sex-sorted semen had relatively little effect on farm profitability per cow, whereas management variables such as conception rate had a significant effect. Profitability was very sensitive to the price of dairy heifer calves, relative to beef and dairy bull calves, for all scenarios studied.

Given this background, and the relative paucity of information relating to seasonal systems, the objective of this research was to determine the relative sensitivity of NP and SSA to key input variables when using sex-sorted semen in a high input–high output, spring-calving, grass-based Holstein-Friesian herd.

MATERIALS AND METHODS

A whole-farm stochastic simulation model was developed for a spring-calving, pasture-based Holstein-Friesian herd. The model was adapted from Butler (2006) but used a spreadsheet-based budgetary framework similar to that of Shalloo et al. (2004). The model structure (illustrated in Figure 1) incorporated a monthly time step to provide a realistic representation of the seasonal profile of livestock inventory flow, fertility parameters, milk production, and feed requirement and supply. Milk supply profiles for cows calving in each month were based on the adapted standard lactation curves of Olori and Galesloot (1999). Feed requirements of cows were modeled through standard equations for net energy requirements for maintenance, milk production, pregnancy, and BW change throughout lactation (Jarrige, 1989). Sufficient dairy heifer calves were reared to meet the replacement requirements of the herd with male and surplus heifer calves sold at <1 mo of age. A standard feeding and management regimen was assumed for dairy young stock based on published guidelines (Kennedy et al., 2011) with heifers calving at 24 mo of age. Heifers rejected due to infertility or other selection factors were assumed sold for beef value only. All biophysical processes were linked to financial equations that quantify economic outcomes in terms of income, balance sheet, and cash flow statements.

The analysis presented here concentrates on projections of the income statement, although balance sheet data are also used to evaluate the consequences of scenarios for ROA. The income statements apply standard accrual-based accounting conventions, and herd valuation changes due to livestock inventory variations and genetic improvement (see below) are therefore included in farm profit. Sales receipts (milk, cull cow, and calf) and variable costs (purchased concentrates, fertilizer, contractor charges, and veterinary) were based on current prices (CSO, 2017; Table 1). Fixed costs (machinery operating expenses, hired labor, depreciation, farm maintenance, phone, electricity, insurance, and professional fees) were average values for specialist dairy farms from the National Farm Survey (Hennessy and Moran, 2016).

Opening asset valuations from the projected balance sheets were used to calculate ROA (i.e., NP divided by total assets). Total assets comprised both fixed and current assets. The fixed assets included the value of land, buildings, and machinery owned, as well as the value of the dairy herd. The valuations for land, buildings, and machinery were based on National Farm Survey (Hennessy and Moran, 2016). The value of the livestock inventory was calculated in the model using market prices. Current assets comprised the estimated values of feed stocks, trade debtors, and bank balance. Based on typical practices, we assumed that a 1-mo supply of concentrate feed was held in stock. Trade debtors comprised the preceding month's milk sales because payment was received 1 mo in arrears. The model was developed in Excel (Microsoft Corp., Redmond, WA) and the primary worksheet comprised 1,126 rows with calculations.

The production parameters for the modeled system were specified from the University College Dublin, Lyons systems herd at Celbridge, Naas, Co. Kildare. This systems herd focuses on farming situations with restricted land availability and targets a high lactation-average yield per cow of >7,500 kg of milk and 625 kg of milk solids (fat and protein), with 75% of the diet (on a DM basis) consisting of grazed grass and grass silage and 1.5 t (1.3 t DM) of concentrates. The system focuses on a compact spring-calving profile, targeting a 6-wk calving rate of 70%; that is, 70% of cows go in calf in the first 6 wk of the mating period (Pierce, 2017). The base calving profile comprised 15, 52, 23, and 10% of the cows calving in the months of January, February, March, and April, respectively.

Reproductive performance through the breeding period was modeled as a Markov process, with calving rate calculated as the product of heat detection rate and pregnancy rate at each ovulation. Maximum number of services was specified for cows and heifers according to normal management practices. Cows and heifers that were not pregnant after the maximum number of services were assumed culled. Therefore, culling rates in the model included the proportion of cows that were not in calf by the end of the breeding period. We assumed that all empty cows were identified through routine ultrasound scanning in the autumn. Furthermore, reflecting management practices for re-

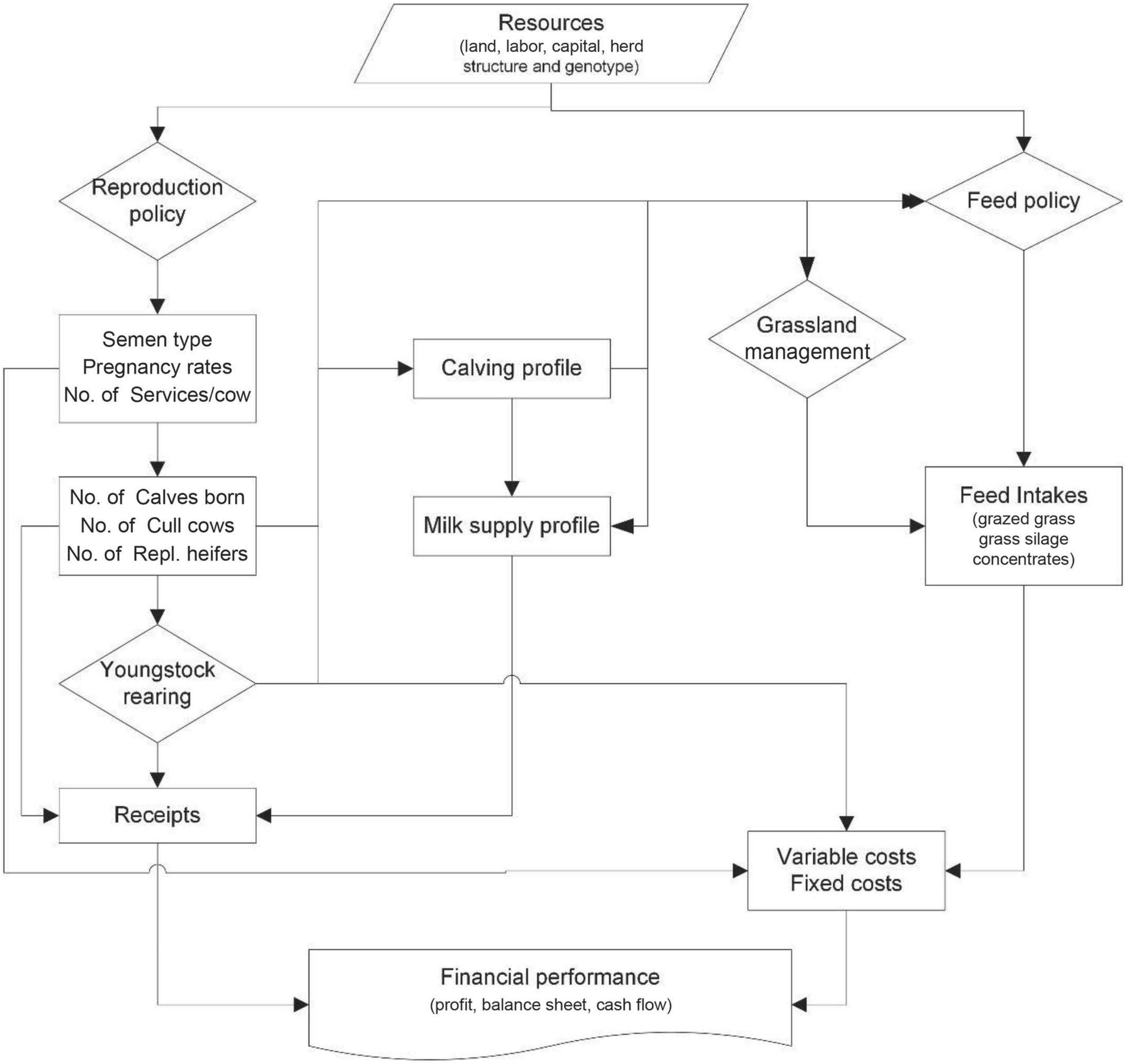

Figure 1. Flowchart illustrating the major components of the dairy simulation model.

tention of a compact spring-calving herd, any cows that calved later than April were assumed not rebred and thus were culled at the end of the current lactation. An additional fixed culling rate of 12%/yr was included to account for other (i.e., nonreproductive) reasons for cows leaving the herd, such as high SCC, lameness, mastitis, and other health or management factors. Furthermore, an annual mortality rate of 4% was applied. These assumptions were derived from national data on dairy culling and mortality rates reported by Maher et al. (2008) and information from a detailed survey of culling decisions by Forbes et al. (1999).

A fixed heat detection rate (AI submission rate) of 85% was assumed in all scenarios according to benchmark management standards for Irish spring-calving systems. In the scenarios with sex-sorted semen, conception rate was reduced to 87% of that for conventional unsorted semen (Butler et al., 2014). We assumed that rates of early embryo loss were constant across scenarios; therefore, reductions in pregnancy rates associated with use

Table 1. Input (normal, truncated) distributions with the mean, minimum, and maximum truncation values

Input parameter	Minimum	Mean	Maximum	Data source
Semen sexing accuracy	0.75	0.90	1.00	Healy et al. (2013); Seidel (2014)
Concentrate price (€/t)	140	280	403[1]	CSO (2017)
Extra cost of sexed semen dose (€)	0.00	20	36[1]	Progressive Genetics (2017)
Standard deviation of index (€)	9.00[1]	105	206[1]	ICBF (2017)
Pregnancy rate cow (unsorted dairy semen) 63–83 DIM	0.15	0.50	0.75	Berry et al. (2003); Butler et al. (2014)
Beef bull calf (€/head)	100	200	383[1]	Irish Farmers Journal (2017a); McHugh et al. (2010)
Beef heifer calf (€/head)	80	160	305[1]	Irish Farmers Journal (2017a); McHugh et al. (2010)
Dairy bull calf (€/head)	12[1]	75	147[1]	Irish Farmers Journal (2017a); McHugh et al. (2010)
Dairy heifer calf (€/head)	100	180	339[1]	Irish Farmers Journal (2017a); McHugh et al. (2010)
Milk fat price (€/kg)	2.50	3.37	6.15[1]	Irish Farmers Journal (2017b)
Fertilizer price (€/t)[2]	242	322	609[1]	CSO (2017)
Heifer:cow pregnancy rate	1.00	1.05	1.30	Butler et al. (2014); DeJarnette et al. (2008); Norman et al. (2010); Hall and Glaze (2014)
Maximum no. of services/cow[3]	2	3	5	Personal experience
Maximum no. of services/heifer[4]	2	3	4	Personal experience
Milk protein price (€/kg)	4.00	6.00	11.14[1]	Irish Farmers Journal (2017b)
Sexed semen pregnancy rate as % of conventional, 63–83 DIM	0.50	0.87	1.00	Butler et al. (2014)

[1] Threshold value determined by the set minimum, mean, and standard deviation values in the assumed @risk (Palisade Corp., Ithaca, NY) distributions. Standard deviations were assumed to be one-fifth of the mean (CV of 20%) for all distributions other than the discrete probability distributions assumed for the number of inseminations per heifer and cow

[2] Reference fertilizer price, per tonne, of composition 25% N, 5% P, 10% K.

[3] No. of services/cow: Discrete {2,3,4,5}, Probabilities {0.35,0.35,0.2,0.1}.

[4] No. of services/heifer: Discrete {2,3,4}, Probabilities {0.4,0.4,0.2}.

of sex-sorted semen were directly proportionate to the assumed reduction in conception rate. The model quantified the effects of changes in pregnancy rates in terms of their impact on culling rate due to infertility and the probable slippage in calving profile. Changes in calving profile were calculated with reference to the base calving profile and were assumed proportional to changes in the distribution of pregnancy rates by service number.

The analysis assumed a fixed dairy herd size of 70 cows, in line with the average herd size among commercial dairy farms in Ireland (Hennessy and Moran, 2016). The area of land owned was 38.5 ha and labor (2,484 h/yr) was supplied by the farmer and his/her family (Hennessy and Moran, 2016). To provide flexibility for the model to accommodate varying numbers of young stock, it was assumed that additional forage area could be rented as required at prevailing land market rents. The NP calculated by the model was family farm income and represented the total return to the farmer and his/her family for their labor, land, and capital used in the business. This financial metric is consistent with the definition of net profit used in Irish farm benchmarking. It is noted that this is an accounting rather "economic" profit because it does not deduct imputed charges for the farmer's own labor, land, or capital. However, this choice was considered inconsequential for contrasts between scenarios because the farmer's own resources of land and labor were held constant in the analysis.

Multiple variables in a farm budget could be varied in a sensitivity analysis of their effects on NP and SSA. We focused on inputs related to those found to be important in the sensitivity analysis of McCullock et al. (2013). The (truncated, normal) input distributions in the @risk (Hyde and Engel, 2002; Palisade, 2017) analyses (100,000 iterations) are shown in Table 1. It was assumed that beef semen was used as a backup on nonpregnant females in later insemination rounds, following standard industry practice. Use of sex-sorted semen was limited to a maximum of 2 services per female, with conventional semen used for any subsequent services.

Three scenarios were modeled: (1) all breeding females inseminated with unsorted semen (**U**); (2) only heifers inseminated with sex-sorted semen (**H**); and (3) both heifers and cows inseminated with sex-sorted semen (**HC**). In scenarios H and HC, sex-sorted semen was used for first and second services only, with unsorted semen used in any subsequent services. In all scenarios, Holstein-Friesian semen was used only in first and second services, with subsequent inseminations using semen from a beef breed. This strategy reflected prevailing management practices to avoid production of dairy replacements from cows with subpar levels of fertility. We note that it would be possible to model a potentially large number of mixed strategies, whereby specific criteria are used to selectively target females for service with sex-sorted semen. This would result in additional scenarios with varying herd proportions of cows or heifers served with sex-sorted semen. We considered that such a range of possible management scenarios would create unnecessary clutter without contributing greatly to our conclusions. Accordingly, for this pragmatic reason, we chose to model "pure" strategies only, with all females in a target group receiving the specified treatment. Each scenario simulation comprised 100,000 iterations and the above 3 scenarios were each given the same sampled value from the input distribution for all inputs unaffected by the use of sex-sorted semen (i.e., feed, milk, and calf prices).

After calculating the economic benefits and costs (operating and fixed) in each month of the year for the herd, the summed annual costs were deducted from the summed annual benefits to obtain annual NP. The sensitivities of NP and ROA to the input variables were studied by using the @risk (Palisade Corp., Ithaca, NY) sensitivity functionality.

The economic benefit of using female sex-sorted semen in a dairy includes the increased selection pressure that can be placed on female replacements so that the female progeny (either kept for breeding or sold) and their descendants have higher genetic or phenotypic merit. As this advantage occurs over several years, discounting methods are needed to calculate NPV. Variables were defined as follows. Subscript i indicates sex (f = female; m = male) and j indicates destiny (b = retained for breeding; s = for sale); c = probability of a semen dose resulting in a calf born (conception rate); x_f = probability of a female calf by X-sorted semen; s_{ij} = survival rate from birth to age at sale or to birth of first progeny; cr = herd calving rate (conception rate from all inseminations × survival rate of embryo to calf); r = herd replacement rate (% of cows replaced each year); p_f = selected proportion of breeding females; PX = proportion of the herd (heifers and cows) inseminated to X-sorted semen; v_{ij} = value of a female/male progeny for breeding/sale; and CX = cost of a dose of X-sorted semen.

The net present value (**NPV**) of a progeny is the difference between their sale price and rearing expenses, discounted at a discount rate δ by a factor d, $1/(1 + \delta)^t$ to time of insemination ($t = 0$). A discount rate of 5% was used, representative of the mean annual interest rate (5.07% ± 1.23) on short- to medium-term business lending (up to 5 yr maturity) in Ireland over the period 2003–2016 (Central Bank of Ireland, 2017). The expected NPV or value of a progeny (v) is the weighted average of the value of sale and breeding animals multiplied by their probability of survival. All male progeny were assumed sold at less than 1 mo of age:

$$v_i = p_i\ s_{ib}\ v_{ib} + (1 - p_i)\ s_{is}\ v_{is}. \quad [1]$$

Sale animal income is already included in gross margin and NP budgets. The value of breeding females resulting from AI ($p_f \cdot s_{fb} \cdot v_{fb}$) was added to income.

When all inseminations (heifers and cows) were by X-sorted semen ($PX = 1$) and no breeding males were retained ($p_{mb} = 0$),

$$v_f = p_f\ s_{fb}\ v_{fb} + (1 - p_f)\ s_{fs}\ v_{fs} \text{ and } v_m = s_{ms}\ v_{ms}. \quad [2]$$

Herd size (milking cows) was assumed to be constant (n = 70), so r female replacements per breeding female enter the herd annually, where $p_f = r/(x_f \cdot cr \cdot s_{fb})$. Standardized selection intensities of females (i_f) were approximated by the expression $0.8 + 0.41\ \ln[(1/p_f) - 1]$ (Madalena and Junqueira 2004), where p_f was recalculated in each iteration for sex-sorted semen scenarios because x_f and PX vary in each iteration.

The expected NPV of a calf (NPV_C) obtained from a semen dose is given as follows:

$$\text{NPV}_\text{C} = c\ [x_f\ v_f + (1 - x_f)\ v_m] = c \cdot v_m\ [1 + (k - 1)\ x_f], \quad [3]$$

where $k = v_f / v_m$.

With perfect sexing (i.e., 100% female offspring; $x_f = 1$), $\text{NPV}_\text{C} = c \cdot v_f$, whereas for non-sex-sorted semen ($x_f = 1/2$),

$$\text{NPV}_{\text{C}(1/2)} = c\ (v_f + v_m)/2. \quad [4]$$

We also included the kept progeny descendants' NPV using the methods of Madalena and Junqueira (2004) and Berry et al. (2006), derived from McClintock and Cunningham (1974) and Van Fleck and Everett (1976) using a 15-yr time frame. The genetic superiority of replacement breeders (b) selected by truncation on a selection index (I) is $\Delta Gib = ib\ \delta I$, where ib = standardized selection intensity of the replacement breeders and δI = the standard deviation of the index. This superiority will be expressed N times (cumulative discounted expressions) in the descendants over the specified time frame. The added NPV of retained female replacements because of selection is $N \cdot i_{fb} \cdot \delta_{\ If}$, so $v_{fb} = v_{f1} + N \cdot i_{fb} \cdot \delta_{If}$, where v_{f1} indicates value of females at first calving. In dairy cattle, adult traits are of interest and likely retained and sold females would probably be sired by the same sires, such that selection of heifers would be based on their dam's index; thus, the additional superiority was calculated as $v_{fb} = v_{f1} + 1/2\ (N \cdot i_{fb} \cdot \delta_{If})$.

Genetic gain contributes to NP through selective breeding for improvement in core profitability traits such as milk production, fertility, and health. In the model, this was captured as the incremental change in herd economic merit measured by the Economic Breed Index (**EBI**) used for genetic selection in Ireland. The EBI indicates the extra profit per lactation expected for a bull's progeny relative to the average (base) cow. The EBI includes 19 traits related to dairy farm profitability, and the economic values (profit contributions) of those performance traits are derived using a standardized methodology for a representative Irish spring-calving dairy system (Veerkamp et al., 2002; Berry et al., 2007). To avoid double counting, our dairy simulation estimated a baseline profit stream excluding genetic gain by assuming a fixed set of technical performance assumptions. We then added the genetic gain as the increase in NPV of retained female replacements according to the cumulative discount expressions described above. This approach circumvented the computational challenges associated with directly simulating a large number of correlated genetic traits. Instead, the profit gain from genetic improvement was established by simulating selection intensity with respect to the national EBI. The financial weightings that are already validated in construction of the index were used to estimate the profit gain through increased selection pressure. The discounted NPV were shown as annual (annuity) equivalent value for ease of interpretation.

RESULTS

Key technical details of the model simulations are shown in Table 2. In the scenarios with sex-sorted semen (H, HC), there was a notable depression in pregnancy rates with resulting slippage in the calving profile. Accordingly, the culling rate under HC was considerably elevated by removals due to infertility (lower conception rates) and remediation of the slippage in calving profile. On the other hand, the increased proportion of dairy heifer calves in the sex-sorted semen scenarios facilitated increased selection pressure in the breeding of herd replacements. Consequently, the potential rate of genetic gain in terms of increase in herd EBI was substantially higher in the scenarios with sex-sorted semen.

Descriptive statistics for the NP distributions are shown in Table 3 for the 3 scenarios. Because of the

Table 2. Summary of key technical details of model simulations

Item	Unsorted semen (U)	Heifers only (H)	Heifers and cows (HC)
Milking herd (cows)	70.0	70.0	70.0
Diet composition (kg of DM/cow per year)			
Grazed grass	2,951	2,960	2,933
Grass silage	1,779	1,789	1,798
Concentrates	1,503	1,509	1,502
Milk production (base year), total for herd			
Milk production (kg)	512,085	511,893	511,194
Butterfat (kg)	23,261	23,253	23,223
Protein (kg)	17,645	17,639	17,619
Pregnancy rate of cows (cumulative % of cows eligible for service)			
First service	46.8	46.8	40.7
First or second service	71.6	71.6	64.8
First, second, or third service[1]	85.4	85.4	81.9
Cows culled for fertility reasons[2] (%)	11.2	11.3	17.7
Pregnancy rate of heifers (cumulative % of heifers eligible for service)			
First service	49.1	42.7	42.7
First or second service	74.1	67.2	67.2
First, second, or third service	87.3	83.9	83.9
Calving profile (proportion of calvings/mo)			
January	0.15	0.15	0.13
February	0.52	0.51	0.46
March	0.23	0.24	0.26
April	0.10	0.10	0.11
May	0.00	0.00	0.01
Calves born by type (average number/yr)			
Holstein-Friesian female	27.5	31.6	45.1
Holstein-Friesian male	27.5	21.7	5.1
Beef cross female	7.0	7.4	8.7
Beef cross male	7.0	7.4	8.7
Genetic gain (average % increase/yr)	1.83	3.33	5.72

[1] Third service assumes unsorted semen in all scenarios.

[2] Not in calf or previous calving date too late.

Table 3. Descriptive statistics for simulated net profit distributions (€ per cow, per ha, per kg of milk and milk solids) for unsorted semen (U), heifers only inseminated with sex-sorted semen (H), and heifers and cows inseminated with sex-sorted semen (HC)

			Percentile	
Group	Mean	SD	5%	95%
Unsorted semen (U)				
€ per cow	1,004	353	445	1,606
€ per ha	1,827	642	809	2,922
€ per kg of milk	13.70	4.80	6.10	22.00
€ per kg of milk solids	1.72	0.60	0.76	2.75
Heifers only (H)				
€ per cow	1,026	352	467	1,624
€ per ha	1,863	639	848	2,950
€ per kg of milk	14.00	4.80	6.40	22.20
€ per kg of milk solids	1.76	0.60	0.80	2.78
Heifers and cows (HC)				
€ per cow	1,068	352	508	1,668
€ per ha	1,939	640	924	3,029
€ per kg of milk	14.60	4.80	7.00	22.80
€ per kg of milk solids	1.83	0.60	0.87	2.86

high number of samples (100,000 iterations), any nonzero differences between scenario output parameters were statistically significant ($P < 0.01$) in paired *t*-tests. Results of the simulations are reported in terms of the estimated mean ± standard deviation of each stochastic output variable. Including the value of genetic gain resulting from the selection intensity, expressed as the NPV of all descendants, added 1.1% ± 1.58, 2.1% ± 1.33, and 4.0% ± 1.63 to the income for the U, H, and HC scenarios, respectively. This resulted in 3.2% ± 22.5, 6.6% ± 39.6, and 12.5% ± 32.3 of the NP being due to genetic gain (per cow, hectare, milk, or milk solids) for the U, H and HC scenarios, respectively. The NP for the U, H, and HC scenarios were €1,827/ha ± 642, €1,862/ha ± 639, and €1,939/ha ± 640, respectively. The ROA were significantly higher when only heifers were inseminated with sex-sorted semen (8.54% ± 2.94) or all females were inseminated with sex-sorted semen (8.85% ± 2.93), compared with 8.38% ± 2.95 when all females were inseminated with unsorted semen.

Key descriptive statistics for the SSA distributions are shown in Table 4 for the H and HC scenarios. The SSA for the H and HC scenarios were €43 ± 60 and €120 ± 90, respectively, which were both greater than zero ($P < 0.01$). The SSA was significantly higher for the HC scenario than for the H scenario.

The relative sensitivities of the range of the NP values in each scenario to the assumed distributions of the key inputs, in rank order, are shown in Table 5. The relative sensitivities of the range of the SSA values to these input distributions are shown in Table 6.

The range in net profit was most sensitive to the assumed distributions of milk protein price (€/kg), milk fat price (€/kg), cow pregnancy rate, fertilizer price (€/t), and concentrate price (€/t) when unsorted semen was used. When only heifers or heifers and cows were inseminated with sex-sorted semen, the range in net profit was most sensitive to the assumed distributions of milk protein price (€/kg), milk fat price (€/kg), fertilizer price (€/t), cow pregnancy rate, and concen-

Table 4. Descriptive statistics for simulated distributions of sex-sorted semen advantage (€ per cow, per ha, per kg of milk and milk solids) for heifers only inseminated with sex-sorted semen (H) or heifers and cows inseminated with sex-sorted semen (HC)

			Percentile	
Group	Mean	SD	5%	95%
Heifers only (H)				
€ per cow	25.32	32.80	−12.64	76.70
€ per ha	43.14	59.70	−25.94	136.64
€ per kg of milk	0.351	0.450	−0.164	1.050
€ per kg of milk solids	0.044	0.060	−0.021	0.131
Heifers and cows (HC)				
€ per cow	67.64	49.80	−1.20	147.41
€ per ha	120.00	90.50	−5.18	265.13
€ per kg of milk	0.942	0.670	0.024	2.017
€ per kg of milk solids	0.118	0.080	0.003	0.252

Table 5. Range of the mean (sensitivity) of net profit (NP; €), extra genetic gain as a percentage of NP, and return on assets (%) to the assumed input parameter distributions for unsorted semen, heifers only inseminated with sex-sorted semen, and heifers and cows inseminated with sex-sorted semen scenarios[1]

	Net profit					
Input distribution	€/cow	€/ha	€/kg of milk	€/kg of milk solids	Extra genetic gain[2] (%)	Return on assets (%)
Unsorted semen						
Milk protein price (€/kg)	955.72	1,738.58	13.06	1.635	3.66	7.97
Milk fat price (€/kg)	668.48	1,216.04	9.14	1.144	2.16	5.58
Cow pregnancy rate (%)	206.45	375.56	2.80	0.351	10.16	1.88
Fertilizer price (€/t)	174.61	317.63	2.39	0.299	1.96	1.45
Concentrate price (€/t)	129.98	236.45	1.78	0.222	1.02	1.08
Heifer:cow pregnancy rate (%)	33.84	61.56	0.46	0.058	2.13	0.28
Maximum services/cow	26.22	47.70	0.36	0.046	5.67	0.35
SD of index	26.21	47.67	0.36	0.045	2.23	0.22
Dairy bull calf (€/head)	20.10	36.56	0.27	0.034	0.73	0.17
Dairy heifer calf (€/head)	17.97	32.69	0.25	0.031	1.09	0.15
Beef heifer calf (€/head)	11.78	21.42	0.16	0.020	0.73	0.10
Maximum services/heifer	10.12	18.41	0.14	0.017	0.72	0.08
Beef bull calf (€/head)	9.93	18.06	0.14	0.017	0.77	0.08
Heifers only						
Milk protein price (€/kg)	956.63	1,737.52	13.08	1.638	9.13	7.97
Milk fat price (€/kg)	666.57	1,210.69	9.11	1.141	6.29	5.55
Fertilizer price (€/t)	179.64	326.27	2.46	0.307	1.59	1.49
Cow pregnancy rate	166.01	301.52	2.26	0.283	3.59	1.54
Concentrate price (€/t)	130.97	237.87	1.79	0.224	1.39	1.09
Sexed semen pregnancy rate (% of unsorted)	56.25	102.17	0.76	0.095	4.34	0.47
SD of index	45.54	82.71	0.62	0.078	4.14	0.38
Heifer:cow pregnancy rate (%)	34.64	62.91	0.47	0.059	2.68	0.29
Dairy heifer calf (€/head)	17.53	31.85	0.24	0.030	1.29	0.15
Dairy bull calf (€/head)	16.55	30.05	0.23	0.028	1.29	0.14
Extra cost of sexed semen (€/dose)	15.54	28.23	0.21	0.027	1.26	0.13
Maximum services/cow	14.93	27.11	0.21	0.026	6.41	0.24
Maximum services/heifer	13.70	24.89	0.20	0.025	0.31	0.11
Beef heifer calf (€/head)	12.30	22.33	0.17	0.021	1.40	0.10
Semen sexing accuracy	11.67	21.20	0.16	0.020	1.35	0.10
Beef bull calf (€/head)	9.76	17.72	0.13	0.017	1.33	0.08
Heifers and cows						
Milk protein price (€/kg)	956.21	1,736.75	13.09	1.638	15.17	7.92
Milk fat price (€/kg)	667.03	1,211.53	9.13	1.143	10.26	5.53
Fertilizer price (€/t)	185.75	337.38	2.54	0.318	3.52	1.53
Cow pregnancy rate (%)	134.20	243.75	1.84	0.230	3.58	1.33
Concentrate price (€/t)	132.80	241.20	1.82	0.227	2.84	1.10
Sexed semen pregnancy rate (% of unsorted)	87.33	158.63	1.16	0.146	1.26	0.84
SD of index	86.38	156.89	1.18	0.148	8.03	0.71
Heifer:cow pregnancy rate (%)	29.06	52.78	0.40	0.050	1.01	0.24
Dairy heifer calf (€/head)	27.17	49.34	0.37	0.046	0.82	0.23
Extra cost of sexed semen (€/dose)	25.14	45.66	0.34	0.043	1.38	0.20
Semen sexing accuracy	24.84	45.11	0.34	0.043	0.93	0.21
Maximum services/heifer	16.73	30.38	0.24	0.030	0.76	0.14
Beef heifer calf (€/head)	14.74	26.77	0.20	0.025	1.04	0.12
Dairy bull calf (€/head)	14.71	26.72	0.20	0.025	0.80	0.12
Beef bull calf (€/head)	9.50	17.26	0.13	0.016	1.01	0.08

[1] This sensitivity analysis shows the impact of each input variable distribution on the dispersion (range of mean) of each output variable. Input variables are ranked by their relative impacts on net profit per cow.

[2] Extra genetic gain is the estimated addition to profit from genetic gain for the herd expressed as a percentage of NP excluding the genetic gain.

trate price (€/t). However, the range in SSA (in NP) when only heifers were inseminated with sex-sorted semen was most sensitive to the assumed distributions of cow pregnancy rate, sex-sorted semen pregnancy rate as a percent of unsorted semen rates, standard deviation of index, additional cost of sex-sorted semen (€/dose), dairy bull calf price (€/head), and dairy heifer calf price (€/head).

DISCUSSION

Use of sex-sorted semen resulted in a higher NP in both the H (€1,026 ± 352/cow) and HC scenarios (€1,068 ± 352/cow) compared with the U scenario (€1,004 ± 353/cow). The relative ranking of the 3 scenarios was the same irrespective of how the NP was expressed, because land area did not change (as forage

Table 6. Range of the mean (sensitivity) of sex-sorted semen advantage in net profit (€) to the assumed input parameter distributions for heifers only inseminated with sex-sorted semen and heifers and cows inseminated with sex-sorted semen[1]

	Sex-sorted semen advantage in net profit			
Input distribution	€/cow	€/ha	€/kg of milk	€/kg of milk solids
Heifers only				
Cow pregnancy rate (%)	62.19	113.54	0.843	0.106
Sexed semen pregnancy rate (% of unsorted)	60.28	109.49	0.814	0.102
Standard deviation of index	21.98	39.84	0.301	0.038
Extra cost of sexed semen (€/dose)	8.11	14.73	0.111	0.014
Dairy bull calf (€/head)	5.71	10.43	0.078	0.010
Dairy heifer calf (€/head)	5.09	9.24	0.069	0.009
Maximum services per heifer	3.87	7.01	0.068	0.008
Maximum services per cow	3.68	6.76	0.049	0.006
Fertilizer price (€/t)	3.29	5.48	0.046	0.006
Concentrate price (€/t)	1.84	3.03	0.026	0.003
Heifer:cow pregnancy rate (%)	1.42	2.64	0.017	0.002
Beef heifer calf (€/head)	1.35	2.44	0.018	0.002
Milk fat price (€/kg)	1.26	4.17	0.016	0.002
Beef bull calf (€/head)	0.93	1.69	0.013	0.002
Semen sexing accuracy	0.88	1.60	0.012	0.001
Milk protein price (€/kg)	0.76	3.30	0.012	0.001
Heifers and cows				
Cow pregnancy rate (%)	96.57	175.95	1.295	0.162
Sexed semen pregnancy rate (% of unsorted)	84.41	153.31	1.121	0.141
Standard deviation of index	62.15	112.80	0.850	0.106
Extra cost of sexed semen (€/dose)	24.44	44.41	0.334	0.042
Dairy heifer calf (€/head)	21.09	38.31	0.288	0.036
Dairy bull calf (€/head)	17.45	31.75	0.239	0.030
Maximum services per cow	16.70	30.41	0.183	0.024
Semen sexing accuracy	14.88	27.01	0.204	0.026
Fertilizer price (€/t)	9.05	15.95	0.126	0.016
Heifer:cow pregnancy rate (%)	6.92	12.64	0.092	0.012
Maximum services per heifer	6.76	12.24	0.108	0.013
Concentrate price (€/t)	3.81	6.61	0.054	0.007
Beef bull calf (€/head)	3.61	6.55	0.050	0.006
Beef heifer calf (€/head)	3.02	5.45	0.042	0.005
Milk fat price (€/kg)	1.69	4.96	0.019	0.002
Milk protein price (€/kg)	1.30	4.34	0.021	0.003

[1] This sensitivity analysis shows the impact of each input variable distribution on the dispersion (range of mean) of each output variable. The output variables indicate the incremental increase in net profit from using sex-sorted versus unsorted semen. Input variables are ranked by their relative impacts on the output variables.

and concentrates were changed to accommodate different lactation requirements and any additional rented land requirement was included as a rental cost) and milk and milk solids were directly related to cow numbers. When the differences in NP between H or HC and U scenarios (i.e., SSA) were calculated for each iteration, very few iterations (subsamples of input combinations) resulted in a negative NP (Table 4). Thus, SSA in NP was significantly positive for both scenarios, being €25 ± 33/cow for H and €68 ± 50/cow for HC. These mean values indicate how much more could be paid for a dose of sex-sorted semen compared with unsorted semen to break even in NP. Inseminating both heifers and cows with sex-sorted semen resulted in a significantly higher NP ($P < 0.01$) than inseminating just heifers and would allow a higher price to be paid for the sex-sorted semen to break even. Khalajzadeh et al. (2012) suggested that an H scenario was superior because reproductive performance (age at first calving, days open, and services per conception) was not so depressed compared with the HC scenario, but they noted the economics need to be considered. We considered both expected reproductive rates and economics and accounted for calving slippage and change in reproductive rates.

Net profit in the U scenario was most sensitive to the assumed distributions of milk protein price (€/kg), milk fat price (€/kg), cow pregnancy rate, fertilizer price (forage cost), and concentrate price (supplement cost) when unsorted semen was used. This order of importance is similar to that found in other studies such as McCullock et al. (2013) and highlights the importance of milk prices and reproductive performance in dairy herds. The range in NP in the H and HC scenarios was most sensitive to similar input distributions (Table

5). In the HC scenario, the extra cost of a sex-sorted semen dose had relatively more effect on the NP range (€24.44/cow) than in the H scenario (€8.11/cow), with more sex-sorted semen doses being used in the HC scenario.

The SSA in the H scenario was most sensitive to the cow pregnancy rate, sex-sorted semen pregnancy rate as a percent of unsorted semen rates, standard deviation of the dairy selection index, additional cost of sex-sorted semen (€/dose), dairy bull calf price (€/head), and dairy heifer calf price (€/head). When cows and heifers were inseminated (HC), the last 2 price inputs were reversed in order of importance. Unlike the situation with regard to NP, milk price became relatively unimportant with regard to the SSA NP range as the milk price had similar effects on NP in all 3 scenarios. Of the input distributions with the highest impact on SSA, base pregnancy rate and number of AI services are the only inputs that dairy producers can directly affect in their herd by their management and decisions. It may be worthwhile, therefore, to undertake a more detailed study of the most economic number of services.

Cabrera (2009) reported that the use of sex-sorted semen was warranted when the conception rate of heifers with conventional semen was 57% or higher and the conception rate with sex-sorted semen was at least 60% of that of the conventional semen (34.2%). That study suggested that the NPV of 1 or 2 sexed services outperformed the NPV of 3, 4, or 5 sexed services. Therefore, based on those assumptions if sex-sorted semen is to be used, a maximum of 1 or 2 services was recommended. Important factors when deciding on whether or not to use sex-sorted semen in order of importance (in relation to NPV) were the conception rate of sexed semen (relative to that of conventional semen) and the cost of sexed semen. Economic factors such as discount rate, value of female and male calves, the daily raising costs of heifers, slaughter value, and replacement costs exerted only marginal influences on the NPV of using sex-sorted semen (Cabrera, 2009). However, Cabrera (2009) noted that estimates of the profit advantage from using sex-sorted semen are sensitive to assumed values of biological (e.g., conception rates) and economic (e.g., calf values, semen costs) parameters. Accordingly, it was proposed that, because of large variability in farm conditions, farm-specific analyses on the feasibility of sexed semen use are justified. The findings of Cabrera (2009) differ from our study and those of Madalena and Junqueira (2004) and McCullock et al. (2013) in that Cabrera (2009) did not find dairy bull or heifer calf prices to be very important, which is unexpected. In addition, Cabrera (2009) did not account for the improved genetic gain resulting from using sex-sorted semen.

Our results are an advance on the studies of McCullock et al. (2013), who did not specify how they calculated increased genetic gain. Because of their computational limitations, they took subsamples from uniform distributions of all key inputs between assumed low and high (threshold) values, which gave all input values the same probability of occurrence. This is unlikely and partly explains why the coefficients of variation of their reported input distributions were very inconsistent across input parameters. In contrast, our study utilized truncated normal distributions for its stochastic variables, thereby recognizing the tendency of the input parameter data points to congregate more densely around their expected (mean) values. We argue that this facilitated more precise simulation of the stochastic input variables and therefore the distribution of financial advantage from sex-sorted semen in a dairy herd.

Madalena and Junqueira (2004) noted that the ratio of female to male calf values, $k = v_f/v_m$, is one of the keys to the value of sex-sorted semen. These values ranked below cow pregnancy rate, sex-sorted semen pregnancy rate as a percent of unsorted semen rates, standard deviation of the dairy selection index, and the additional cost of sex-sorted semen (€/dose) in importance in our study. Madalena and Junqueira (2004) did not account for some of these factors in their analyses. The ratio of female to male calf values could be used as an input in budgetary models but it is more usual to include each value and price separately as we have done. Calf values were included among the key parameters by McCullock et al. (2013). When both sexes have equal value ($k = 1$), there is no benefit in sexing; otherwise, the value expected from a semen dose increases or decreases with x_f, by $c \cdot v_m\ (k - 1)$. We found that the relative importance of female to male calf values varied with scenario so it is not recommended to use a ratio to understand their individual impacts.

Noonan et al. (2016) noted that using methods that increase conception rates from sex-sorted semen will give dairy producers the potential to increase the number of replacement heifers from a smaller proportion of the herd, help to offset poor fertility, accelerate genetic gain within the herd, and reduce the number of bull calves. Further advantages might include diverting resources from the need to produce replacement heifers toward more profitable ventures, an increased ability to run a closed herd, thus improving herd biosecurity, and a welfare improvement through a decrease in the incidence of dystocia, as female calves typically have a lower birthweight than males. There are also some disadvantages in using sex-sorted semen, especially in seasonal dairy systems. In particular, our model identified the issue of calving slippage and consequently lower utilization of grazed grass as the least-cost feed source. Notably, under HC, the calving period increased by 1 mo, concluding in May rather than April, as in the U scenario. From a management perspective, the widening calving distribution is suboptimal for a spring block-calving herd in Ireland, where a compact calving profile concentrated on early February is generally most profitable (Shalloo et al., 2004). Nonetheless, our analysis found that the negative effects associated with calving profile slippage in the sex-sorted semen scenarios were offset by the financial benefits in terms of enhanced calf values and rates of genetic gain.

Madalena and Junqueira (2004) found that the contribution of increased selection intensity on dam index to the value of sex-sorted semen was rather small in their dairy examples. The increased value of the replacement heifers caused by the more intense selection practiced with sex-sorted semen was partly offset by a lower number of future discounted expressions from replacement descendants, because of the lower chance of a heifer entering the herd when more of them were available. For example, for conception rate = 0.67, the proportion of heifers retained was 0.55 with non-sex-sorted semen ($x_f = 1/2$) and half of that with perfect sexing ($x_f = 1$), which increased the genetic merit in the latter case by US$4.8. However, the number of discounted lactations of a heifer progeny entering the herd was reduced from 7.5 to 4.9, so the genetic merit added a similar proportion to the value of the replacement heifer in both; that is, 0.30 and 0.32, respectively. Cunningham (1975) noted that the relative contribution of the dam to daughter path on genetic transmission was only 5% but, due to the shorter time lag, its relative economic importance was 13%, still much less than the impact of sires with their higher numbers of offspring. We model a 1-yr window of insemination with the same superior AI dairy bulls used on heifers and cows. The genetic merits of different age groups are not differentiated in the methods of Madalena and Junqueira (2004). The NPV and genetic gain are moderately higher in the HC versus H scenario because more heifer calves (with higher values than bull calves) are produced that result in a higher selection intensity of females in subsequent matings. The standardized selection intensities (i) were 0.35, 0.50, and 0.82 for the U, H, and HC scenarios respectively, so the value of genetic gain was highest for HC.

We found the contribution of increased genetic value to income was 2 to 4% in the H and HC scenarios compared with only 1.1% in the U scenario. The variance of the dairy selection index (EBI), however, was the third most important input distribution affecting SSA, so the value of increased selection intensity in terms of SSA can be large when the extreme EBI values possible from the assumed EBI distribution are used in any iteration.

Ettema et al. (2017) noted that genetic gain is greater when sexed semen is used on genetically superior females. If regular genetic gain is being made, then the proportion of superior females would be higher in younger generations (i.e., heifers) than in cows. When there is a poor market for surplus heifer calves, Ettema et al. (2017) suggested counterbalancing the use of sexed dairy semen in heifers with the use of beef semen in cows to limit the size of the young stock herd. They found that net return increased up to €18 per slot when using sexed semen in 75% genetically superior heifers and beef semen in 70% genetically inferior, multiparous cows. The assumed reliability of selection was 0.84. They did not compare inseminating 75% genetically superior heifers with inseminating all heifers or all heifers and cows with sexed semen.

Madalena and Junqueira (2004) noted that selling older animals yields a greater advantage from using sex-sorted semen. However, raising more surplus animals changes the allocation of farm resources to the different categories, which may or may not be economical. For example, a dairy farm using sex-sorted semen needs land and resources to raise the increased number of heifers before sale. To assess whether those resources would be better allocated to heifers or to milking cows required a system analysis beyond the scope of their paper. We assumed that all surplus calves were sold within 1 mo and did not assess the economics of selling surplus stock at a later age.

We found that pregnancy rates had a critical effect on SSA. Madalena and Junqueira (2004) also noted the overriding effect of conception rate on the potential benefits from semen sexing. Artificial insemination will not be economic when fertility is low, and this is reflected in Equation [3], where the expected NPV of a progeny by a semen dose is proportional to the conception or pregnancy rate. Seidel (2014) reported that with excellent management, pregnancy rates in cattle with 2 million sex-sorted sperm per insemination dose are about 80% of those with conventional semen at normal sperm doses.

Dairy farmers often keep almost all their newborn heifer calves despite the high cost of rearing. By rearing all heifer calves, farmers have more security and retain flexibility to cope with any potential uncertainty surrounding the availability of replacement heifers. This uncertainty is due to mortality or infertility during the rearing period and the variation in culling rate of lactating cows. However, Mohd Nor et al. (2015) found that, under Dutch dairy farming conditions, it was not financially optimal to keep all heifer calves. Similarly, in our analysis, we assumed that the proportion of females retained was closely matched to the requirement for herd replacements after including provision for anticipated heifer mortality rates, infertility, and managerial selection factors. Consequently, the model minimized replacement costs by avoiding the retention and rearing of heifers that would be surplus to herd requirements. We acknowledge that this differs from the observed practice of many dairy farmers who choose to rear all heifer calves and accept higher rearing costs as the price of greater flexibility.

Hess et al. (2016) found that calf sex primarily influences milk yield through increased gestation length of male calves and bias associated with the interval centering method used to estimate whole-lactation milk yields. They proposed that including information on calf sex is unlikely to have an effect on selection response in dairy cattle so we did not include this effect. The use of sex-sorted semen used in combination with crossbreeding in Finnish dairy herds was found to be an economically efficient strategy for increasing dairy beef production (Hietala et al., 2014). Future studies may be extended to study the use of sex-sorted semen in crossbreeding herds.

Results from our study indicate that the use of sexed semen has the potential to improve the NPV of dairy enterprises; however, the current uptake of sexed semen in commercial Irish dairy herds is low. The main reason for this may be that only a limited number of bulls have sex-sorted semen available, and not all of the highest ranked bulls based on genetic merit are currently available. However, this may change as farmers become aware of the improved profitability that can be achieved by using sex-sorted semen and demand for sex-sorted semen grows, thus encouraging AI companies to provide sex-sorted semen from a wider range of bulls.

Several limitations of the present study are noted in relation to aspects of model and scenario specifications. First, the model's representation of system dynamics in a steady-state form and using a monthly time step may not fully capture more subtle effects of the sexed-semen scenarios, especially in relation to slippages in calving pattern. Moreover, the steady-state formulation meant that the resource parameters (e.g., dairy herd size) were held constant and the model was solved for all periods simultaneously. Accordingly, variables such as pasture supply and utilization were assumed accurately forecasted by the farmer. In practice, farmers make decisions with imperfect information and must routinely make tactical adjustments to control for deviations between planned and realized conditions. Incorporation of these more nuanced aspects of decision-making would greatly add to model complexity by requiring a sequential solution procedure. In this context, a more granular specification of the planning horizon to either a weekly or a daily time-step would be required to allow more precise simulations of system dynamics. However, in the context of the present study, we considered that such extensions would add limited extra insight while greatly adding to model complexity and data challenges associated with parameterization. Similarly, the steady-state formulation permitted the model to readily match supply with demand for replacements given assumptions such as a fixed age at first-calving, defined mortality rates, and predetermined culling rules. In practice, these factors are subject to predictive variability and therefore farmers may need to retain a greater number of "surplus" heifers as a margin of safety. Actual practices will also depend on the farmer's management preferences and degree of risk aversion. Unfortunately, treatment of these factors remained outside the scope of the present analysis.

Second, we limited our attention to pure (all or nothing) strategies. Consequently, an area of further development could focus on more flexible mixed strategies based on management criteria for targeted selection of females for application of sex-sorted semen. In accordance with De Vries (2017), the profit advantage of sexed-sorted semen is likely to be greatest for genetically superior females in the herd. Such targeted approaches deserve further investigation and can be addressed with some natural extensions of the model to allow simulations at the animal level as well as the herd level.

Third, our simulation of the NP increase from genetic gain based on selection intensity with respect to EBI was arguably "broad-brush." However, this was also a practical and coherent response to the complex modeling problem associated with simulating multiple traits. Ramsbottom et al. (2012) conducted a validation study using a large data set of 1,131 commercial herds with data on both profitability and genetic merit. They concluded that "the change in herd profitability per unit change in herd genetic merit for the total merit index was within expectations." Nonetheless, simulation of the profitability impacts of genetic gain is an area that merits future refinements toward more detailed and integrated modeling of genetic traits.

CONCLUSIONS

This study identified a significant profit advantage to using sex-sorted semen in the context of a high-output, spring-calving dairy system in Ireland. This financial advantage was largest in a scenario where both heifers and cows—rather than heifers only—were inseminated with sex-sorted semen. The financial advantage of sex-sorted semen was most sensitive to (1) base pregnancy rate, (2) sex-sorted semen pregnancy rate, and

(3) standard deviation of the breeding selection index. The importance of base pregnancy rate indicated that use of sex-sorted semen is better suited to farms that already have good fertility performance. The lower conception rates associated with sex-sorted semen may be less acceptable for farms with suboptimal dairy herd fertility. However, continuing improvements in sorting technology may narrow the gap in conception rates for sex-sorted versus conventional semen, thereby lessening this constraint into the future. Use of sex-sorted semen facilitates more rapid genetic progress through increased selection intensity. The rate of genetic gain is a function of the breeding selection index; consequently, the value of increased selection intensity rises with variance of the breeding index. However, our analysis showed that the income contribution of increased genetic gain was actually quite modest, with the main financial advantage of sex-sorted semen arising from enhanced sales values for young stock.

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